AD-A168 746 HUMAN EXERCISE AND HEAT EXCHANGE IN THERMAL ENVIRONMENTS(U) ARMY RESEARCH INST OF ENVIRONMENTAL MEDICINE NATICK MA M N SAWKA ET AL. MAY 86 1/1

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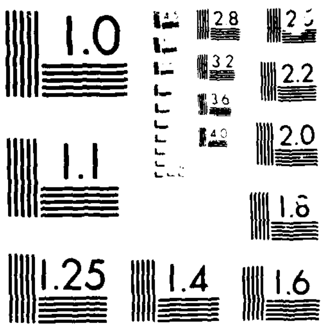
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HUMAN EXERCISE AND HEAT EXCHANGE IN THERMAL ENVIRONMENTS

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REPORT DOCUMENTATION PAGE

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1. REPORT NUMBER M35/86	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) Human Exercise and Heat Exchange in Thermal Environments		5. TYPE OF REPORT & PERIOD COVERED
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Michael N. Sawka, Andrew J. Young, C. Bruce Wenger and Kent B. Pandolf		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS U.S. Army Research Institute of Environmental Medicine Natick, MA 01760-5007		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 3E162777A879BD WU 127
11. CONTROLLING OFFICE NAME AND ADDRESS Same as 9. above		12. REPORT DATE May 1986
		13. NUMBER OF PAGES 9
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report)
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

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17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Biomedical instrumentation; Bioengineering; Heat stress; Cold stress; Exercise, Human temperature regulation

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The thermal-physiological strain imposed by an exercise-environmental condition depends upon the individual's metabolic rate and the capacity for heat exchange with the environment. In hot environments, applied physiology issues concerning the capacity of humans to thermoregulate include the influence of an individual's acclimation state, aerobic fitness, hydration level, and circadian rhythms as well as the type of physical exercise performed. In cold environments, issues include further investigation of human cold acclimation, as well as the

influence of body fat and exercise type on the resistance to hypothermia during cold water exposure. Emerging instrument/engineering technologies for the measurement of core temperature, sweating rate, skin blood flow and shivering offer promise for studying physiological responses in different environments.

ABSTRACT

The thermal-physiological strain imposed by an exercise-environmental condition depends upon the individual's metabolic rate and the capacity for heat exchange with the environment. In hot environments, applied physiology issues concerning the capacity of humans to thermoregulate include the influence of an individual's acclimation state, aerobic fitness, hydration level, and circadian rhythms as well as the type of physical exercise performed. In cold environments, issues include further investigation of human cold acclimation, as well as the influence of body fat and exercise type on the resistance to hypothermia during cold water exposure. Emerging instrument/engineering technologies for the measurement of core temperature, sweating rate, skin blood flow and shivering offer promise for studying physiological responses in different environments.

INTRODUCTION

Man performs muscular exercise in thermally stressful environments for reasons of survival, vocation or recreation. The magnitude of thermoregulatory strain imposed by an exercise-environmental stress is dependent upon the individual's metabolic rate and capacity for heat exchange with the environment. Muscular exercise can increase metabolism by 10 to 20 times the basal rate with the majority of energy expenditure resulting in metabolic heat release, most of which is convectively transferred via the venous blood to the body core. Thermoreceptors in the skin and body core provide input into the hypothalamic thermoregulatory center where this information is processed, via a proportional control system, with a resultant signal for heat loss, or gain, by the effector responses of sweating, shivering and alterations in skin blood flow. The ambient conditions (e.g., dry-bulb temperature, dew-point temperature, air velocity) in which an individual performs exercise will influence the avenues of heat exchange between the skin surface and the environment. In general, muscular exercise and heat stress are synergistic whereas muscular exercise and cold stress tend to counteract one another.

Our research group has a long-term interest in the applied physiology of exercise at environmental extremes on humans. This paper will briefly review current and emerging applied physiology issues, as well as their related instrumental-engineering issues, concerning human exercise and heat exchange in both hot and cold environments.

APPLIED PHYSIOLOGY ISSUES

Traditional Areas

During muscular exercise in the heat, human thermoregulatory responses are traditionally believed to be influenced primarily by acclimation state (1), aerobic fitness (2) and hydration level (3). Aerobically fit persons who are heat acclimated and fully hydrated will have less body-heat storage and optimal performance during exercise-heat stress (3).

Heat "acclimation" refers to the physiological adaptations which occur (during a relatively brief period) to reduce the thermal strain imposed by an experimentally induced exercise-environmental stress. Heat acclimation can be induced by daily 100 min exposures to exercise-heat stress over a 5-10 day period. The physiological changes associated with heat acclimation include an expanded blood volume, reduced electrolyte loss in sweat, improved sweating, improved skin blood flow, and lowered heart rate during exercise in the heat. Possibly the most important recent finding is that heat acclimation reduces the threshold temperature for thermoregulatory sweating and that aerobic fitness training increases the gain of that effector response (1). Those results indicate that heat acclimation and aerobic fitness training exert differential actions on the thermoregulatory control system. One emerging research topic is the magnitude of, and physiological mechanisms responsible for the heat-acclimation-induced reduction in metabolic rate during exercise-heat stress (4,5). Young _et al_. (6) have shown that the reduction in metabolic rate is associated with muscle glycogen sparing and reduced muscle lactate. These findings suggest that heat acclimation may alter motor unit recruitment patterns during exercise. Future research also needs to determine if man acclimates differently to hot-dry (desert) and hot-wet (tropic) environments, and to determine the physiological mechanisms responsible for any differences found.

Finally, additional research needs to be directed toward cardiovascular adaptations during heat acclimation.

Aerobically fit individuals experience less physiological strain (e.g., lower heart rate and core temperature) than unfit individuals during exercise-heat stress (2). In addition, they will acclimate to heat more rapidly and retain that level of heat acclimation longer than their unfit counterparts. A recent study has demonstrated that training *in cold water* can increase aerobic fitness *without* improving thermoregulatory responses during exercise-heat stress (6). These data indicate that it is not aerobic fitness *per se* that improves thermoregulatory function, but it is the repeated increase in core temperature encountered during exercise training. Individuals with high aerobic fitness are also able to tolerate a very high core temperature level during exercise. Future research should determine the physiological-neurochemical mechanisms which enable the very fit to continue exercise during marked hyperthermia.

Hypohydration increases heat storage during exercise and reduces endurance in comparison to euhydration levels (3). The greater heat storage is attributed to decreases in sweating rate and skin blood flow. These decreases in effector responses have recently been attributed to both plasma hyperosmolality and hypovolemia (7,8); however, the central and peripheral sites of their action need to be elucidated. Some new findings are that hypohydration may neutralize the thermoregulatory advantages conferred by both aerobic fitness (9) and heat acclimation (10). Hydration level may thus be the most important single biomedical factor determining an individual's ability to tolerate exercise-heat stress. Some emerging areas of interest are the effects of exercise-heat induced hypohydration on plasma volume (8,11) and the fluid regulatory hormones (12,13). Future research will also need to address how the decrease in total body water during hypohydration is partitioned between the body fluid compartments.

Emerging Areas

It is well documented that resting individuals have a circadian pattern for core temperature, with the minimum and the maximum values occurring in the early morning and evening hours, respectively. Several researchers (14,15,16) have recently investigated the effects of circadian rhythm on core temperature and thermoregulatory effector responses during exercise-heat stress. Both thermoregulatory sweating and peripheral blood flow responses during exercise are altered by time of day. Likewise, the menstrual cycle also influences thermoregulatory responses to exercise in the heat (16). Another recent study indicates that sleep loss will cause less efficient thermoregulatory responses during exercise (17). It is clear that the effect of circadian rhythm, menstrual cycle and prolonged wakefulness on thermoregulatory responses to exercise are exciting new investigative areas.

Another new concept is that how an individual thermoregulates might depend upon the specific skeletal muscle group employed for the exercise task (18,19). Thus, different thermoregulatory responses may be elicited during arm exercise as opposed to leg exercise. This information has profound implications for disabled individuals, who must use their upper body muscle groups for locomotion, and may have a reduced ability to thermoregulate as a result of their disability. Also, future research should determine the thermoregulatory impact of an isometric exercise component upon a predominantly dynamic exercise task, a situation common to many real-life activities.

There are several important new findings concerning human physiological responses to cold stress. The existence of a cold acclimatization process (which is developed over several years) has long been demonstrated. However, Park _et al._ (20) have recently shown that this cold acclimatization could be lost. Korean divers who recently started using wet-suits to reduce cold stress appear to have

lost much of their cold acclimatization (20). This observation of deacclimatization suggests that humans may be capable of short-term cold acclimation. Subsequently, Young et al. (21) demonstrated that humans can acclimate to cold over a period of several weeks, primarily through vasomotor adjustments which increase body insulation. The topic of human cold acclimation will probably develop into an important new area of research.

The study of human thermal responses to acute cold water immersion during both rest (22,23) and exercise (19,22) has received attention. Recent findings indicate that water temperature, subcutaneous fat and exercise type are better predictors of hypothermia than body mass, surface area-to-mass ratio and gender during cold water immersion (19,22,23). The use of cold water immersion to experimently induce hypothermia has gained favor because it elicits a fairly predictable and rapid drop in body temperature without the risk of peripheral tissue injury.

INSTRUMENTATION/ENGINEERING ISSUES

The fundamental instrument/engineering issues concern refinement of methods to quantify components of the energy balance equation in laboratory and field situations. These instruments not only have to be accurate and reliable, but, by the nature of the problems, they must function under extremes of ambient temperature and humidity. It is not uncommon to have an instrument perform precisely in a 20°C environment, but fail during experiments in a 40°C environment. Likewise, for hypothermia studies the instrument's sensor might need to function precisely and safely at subfreezing temperatures or while immersed in water.

Core temperature is usually measured at either the rectum, esophagus, or tympanum/ear canal. The merits and disadvantages of each measurement site are well understood. Rectal temperature responds slowly and tympanum/ear

canal temperature is biased by skin temperature. Esophageal temperature is the laboratory measurement of choice, but many individuals find that the esophageal catheter is uncomfortable and this measurement site may not be practical for many field situations. Recently, interest has been directed toward the development of a temperature sensing "pill" that would emit a signal to be telemetered and amplified. The development of such a system would have a marked influence on field research efforts in industrial and military settings.

Body evaporative cooling is usually calculated from changes in nude body weight, which are used to estimate sweating rate during exercise-heat stress. Perhaps the most important recent instrumentation advancement was the development of a small automated dew-point temperature system, using a miniature Peltier module, to measure local sweating rate (24). Compared to the traditional resistance hygrometry, this new instrumentation seems to have gained instant favor from thermal physiologists (15,16,17,18).

Quantification of dry heat exchange is generally obtained by use of heat flow disks (17,18,19,22) to calculate skin heat conductance. Heat flow disks, however, may alter (by their presence) the variable they are measuring. Skin blood flow is usually measured by venous occlusion plethysmography (7,14,15,16). This technique, however, requires considerable operator and subject expertise. Some recent interest has been directed toward the use of a laser-doppler flowmeter (25) to measure skin blood flow during exercise. This new methodology needs to be further validated against traditional methods such as venous occlusion plethysmography or radioactive microsphere clearance, but seems to be technically simple and provides promise.

Determination of aerobic metabolic rate (oxygen uptake) and therefore metabolic heat release is usually measured by open-circuit spirometry. In the laboratory, oxygen uptake measurements can be obtained for almost any

experimental requirement. In the field, however, new technologies need to be developed that employ light-weight and rugged equipment capable of performing serial measurements. During cold stress, shivering is one thermoregulatory effector employed to defend core temperature. Traditionally, shivering is quantified by the increase in oxygen uptake above control levels or by visual observation. A recent innovation is the use new the electromyographic (EMG) signal to study shivering. However, quantification of shivering by the EMG signal is difficult, and power spectral analysis is one new method used to quantify shivering during cold stress (26).

In conclusion, thermal physiologists currently favor transient forcing function analyses of thermoregulatory responses to exercise-thermal stress. During these transient analyses, the thermoregulatory effector response to a given thermal drive (e.g. core temperature) is evaluated. This requires accurate and rapidly responding measures of core temperature, sweating, skin blood flow and shivering. In this regard, both dew-point hygrometry and laser-doppler velocimetry are promising technological advances.

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